PORE PRESSURE EFFECTS IN BOREHOLE SHEAR TESTING

by

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ABSTRACT: The effects of excess pore pressures on shear strength results obtained using the Borehole Shear Test (BST) were investigated. Pore pressures were measured during the consolidation, shear, and post-shear phases of the test for both stage testing and fresh shear testing. Results indicate that in the clays tested, higher pore pressures were generated during fresh shearing. A consolidation time of 20 minutes was necessary to dissipate excess pore pressures. Pore pressures measured during shearing were used to obtain effective shear strength parameters.

INTRODUCTION

In recent years, the Borehole Shear Test (BST) has been gaining popularity among practicing geotechnical engineers for assessing the shear strength of soils in place. One of the problems associated with interpreting the results of the BST has been the influence of pore water pressure during various phases of the test. This has particularly been of concern when testing clays. In order to assess this problem, an experimental study was undertaken to determine pore pressure effects by measuring pore pressure on the face of the shear plate for both stage testing and fresh shearing. Pore pressures were measured at two locations on the shear plate in order to give some indication of the distribution of pore pressure across the shear plate during the consolidation phase, shear phase, and post-shear phase of the test. The purpose of this paper is to present some preliminary results of the work and discuss correction of the data to obtain the effective parameters ϕ' and c'. Additionally, a brief discussion of the potential for using the results from the consolidation phase to estimate the one-dimensional coefficient of consolidation is presented.

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BST AND PORE PRESSURE

Within the realm of in situ testing the BST presents a unique solution to measuring shear strength; i.e., the measurement of both cohesion and friction angle. A question which has often been asked regarding the BST is "does the test measure drained or undrained strength parameters, or are the results somewhere in between?". In soils which drain rapidly or are unsaturated, the interpretation of BST results has generally not been a problem in that there is no pore pressure generated. However, in saturated clays, there may be a strong tendency to generate excess pore pressure during either the consolidation or shear phase of the test, in which case the interpretation of the results has been open to controversy.

A valuable investigation into this problem was reported by Demartinecourt and Bauer (2) who conducted BST's in soft sensitive marine clays. Excess pore pressures were measured at the center of the shear plate using a porous stone-transducer readout system. The results of this work showed that a large amount of excess pore pressure could be generated during the consolidation phase of the test, which meant that a long time (up to 3 hrs.) might be required to totally dissipate the excess pressure before the shear phase of the test could begin. For drained conditions, the shear phase had to be conducted slowly so that pore pressure didn't develop. In order to obtain a complete drained envelope, the time investment would probably offset the advantages gained by testing in the field.

TESTING PROGRAM

The work described herein is part of a larger study currently being conducted to investigate various aspects of the BST. A standard 76mm (3 in.) diameter BST shear head was modified to accept two porous stone-transducer systems as shown in Fig. 1. The purpose of placing two stones on the shear plate was to provide an estimate of the distribution of pore water pressure across the shear plate during the consolidation and shear phases of the test. Sintered-metal porous stones of 6.4mm (0.25 in.) diameter connected to submersible pressure transducers were used to measure pore pressure. Glycerol was used as the pressure fluid to help ensure a saturated system. Calibrations for each system were obtained by placing the shear plate into a water-filled triaxial chamber and connecting the systems to an external transducer mount using the same length of nylon pressure tubing as used in the field. Prior to each field test, both stones were backflushed and resaturated.

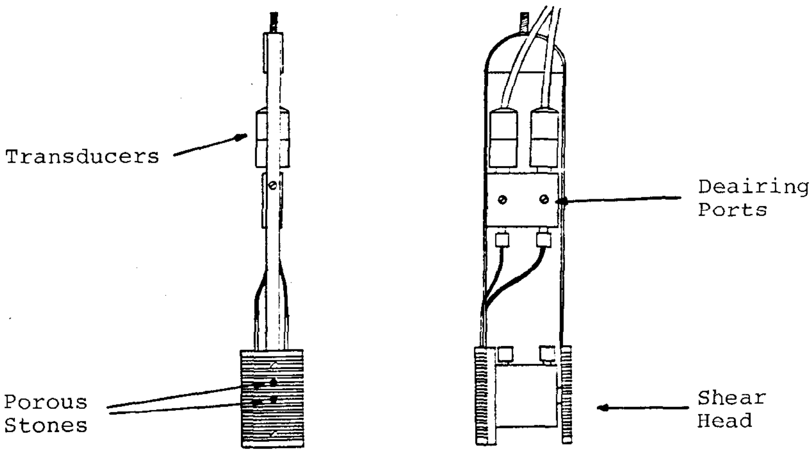

FIG. 1. - BST Shear Head for Measuring Pore Pressure

Tests were conducted at two research sites in Massena, N.Y., where previous test borings indicated that the soils consisted of moderately and lightly overconsolidated marine clays of moderate sensitivity. Generalized soil properties of the sites are shown in Fig. 2. Tests were conducted at 0.8m (2.5 ft.) intervals down to a depth of 3m (10 ft.).

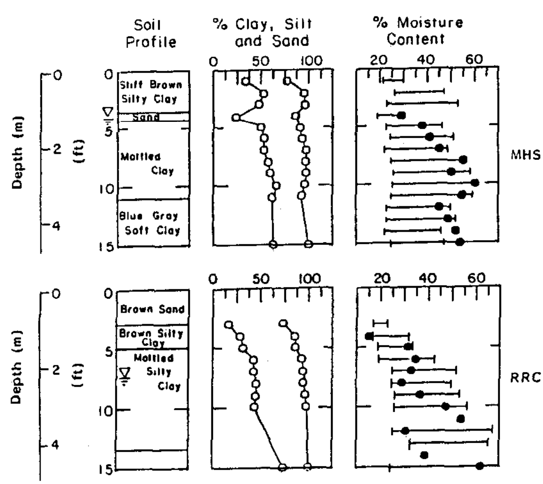

FIG. 2. - Geotechnical Characteristics of Test Sites

The results described by Demartinecourt and Bauer (2) were for fresh shearing only, as they did not feel that the technique of stage testing would be applicable to the sensitive soils being tested. The authors considered it of some importance to make a check of this and therefore it was decided to conduct parallel tests using both stage testing and fresh shearing in order to compare the results. During stage tests, the successive increases in normal stress are applied to the soil without relocating the shear head in the borehole. In fresh shearing, the shear head is removed after each test point, cleaned, and repositioned to a fresh location in the borehole for the next increment of normal stress.

Tests were conducted in three phases: (1) consolidation phase, during which pore pressure dissipation vs. time was measured; (2) shear phase, during which pore pressure, shear force and shear displacement were measured; and (3) post-shear phase, during which pore pressures generated in the shear phase were allowed to dissipate after peak shear stress had been attained.

Linear regressions were used to obtain individual failure envelopes and included all data points for fresh shear tests. However, for stage tests, the initial test point was not used in the regression since this point does not represent stage testing.

RESULTS

Pore Pressure Measurements

For each shear envelope, at least four data points were obtained at varying levels of normal stress. Therefore, for the sixteen tests reported in Table 1, 48 consolidation, shear and post-shear pore pressure curves were available for review. The general trend in results will be summarized by considering the data from one of the test series (MHS 3.0m) as typical. Results from the stage testing and fresh shearing will be described for various phases of the test.

Consolidation Phase

During the consolidation phase of the test excess pore pressures generated after application of the normal pressure should be allowed to dissipate to hydrostatic conditions before initiating shearing. In spite of the care exercised in deairing the porous stone systems, maximum pore pressures were not measured instantaneously but increased within the first minute of the test. Initially, it was thought that this condition may be the result of trapped air in the fluid lines, however instantaneous response was observed when submerging the shear head below the static water table. The consolidation curves shown in Fig. 3 indicate some typical trends observed in the clays tested which may be summarized:

(1) At a given applied normal stress, the maximum excess pore pressure is greater (usually 2-5 times) in fresh shear than in stage testing.

(2) During stage testing, the excess pore pressure is nearly identical at the center and the third point of the shear plate.

(3) During fresh shear tests, the excess pore pressure at the center of the shear plate is less than at the third point.

(4) The rate of dissipation for both porous stone locations is generally about the same for either stage testing or fresh shearing.

(5) The rate of dissipation appears to be greater for fresh shearing, however the total consolidation time is generally less for stage testing.

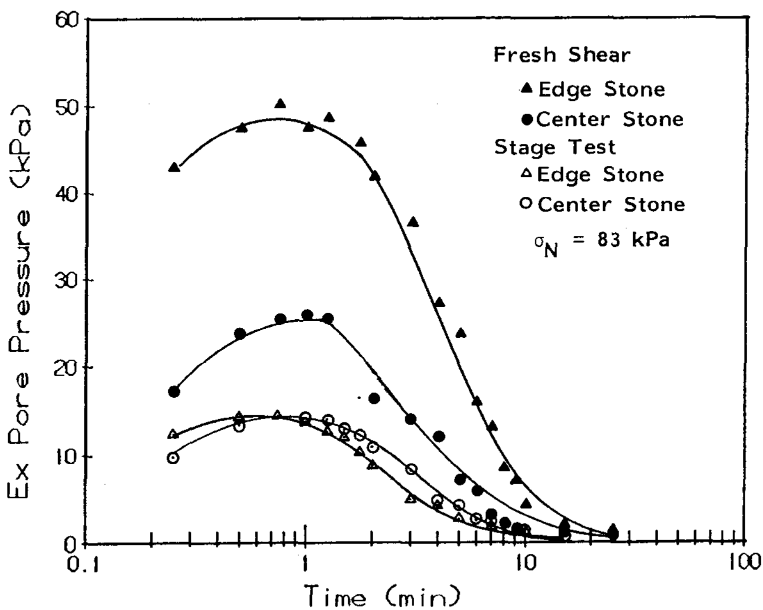

FIG. 3. - Consolidation Phase Results

The behavior described above is characteristic for the tests conducted. Based on these observations, it seems that stage testing might offer some distinct advantages over fresh shearing apart from those described by earlier work (5,6). In general, it would appear that: (1) more uniform pore pressures are generated across the shear plate, which produces more uniformly consolidated soil; (2) less excess pore pressure is generated; and (3) consolidation time is reduced. However, it would also appear that the 5 min. consolidation time recommended by the manufacturer is too short and should be doubled, at least for clay soils.

Shear Phase

Very little work has been conducted to determine correct shear rates for the BST. The authors elected to use one-half the manufacturer's recommended rate of two revolutions per second, which corresponds to a shear displacement of about .025 mm/sec. (.001 in./sec.). The advantage of measuring pore pressures during the shear phase of the test is that potentially both total stress and effective stress parameters may be obtained. Shear displacements were measured using a dial indicator attached to the pull rods. Typical curves of pore pressures generated as a function of shear plate displacement are shown in Fig. 4. Only measurements taken up to the point of maximum shear stress are shown.

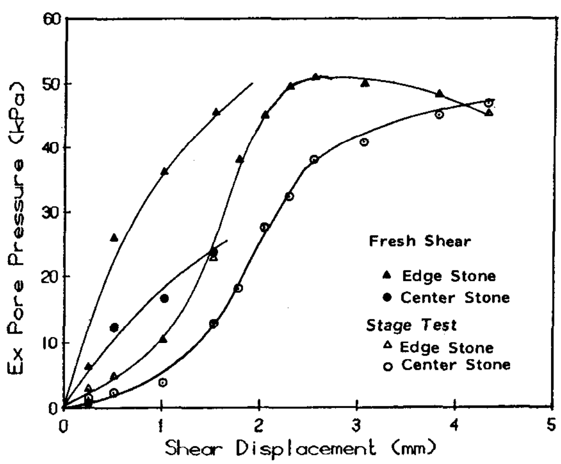

FIG. 4. - Shear Phase Results

Pore pressures at the center of the shear plate were nearly always less than at the upper third point for both fresh and stage shearing. This may be an indication of plowing or bulldozing of material in front of the shear plate. Shear displacements to obtain peak shearing stress were generally less than 2.5 mm (0.10 in.). These results indicate that during the shear phase, effective normal stresses across the shear plate are nonuniform and therefore an average value must be used for reducing results.

Post-shear Phase

Following peak shear, at which point shear phase pore pressures were at a maximum, the shearing force was released and the pore pressure allowed to dissipate. As shown in Fig. 5, post-shear reconsolidation curves all have the same general shape, regardless of porous stone location and test type. Nearly 20 min. was required to totally dissipate excess pore pressure generated during shear. This characteristic is an important discovery which has not been previously reported and suggests that, in a stage test, sufficient time should be allowed for the failure surface to reconsolidate or "heal" following the shear phase to prevent a localized bearing capacity failure.

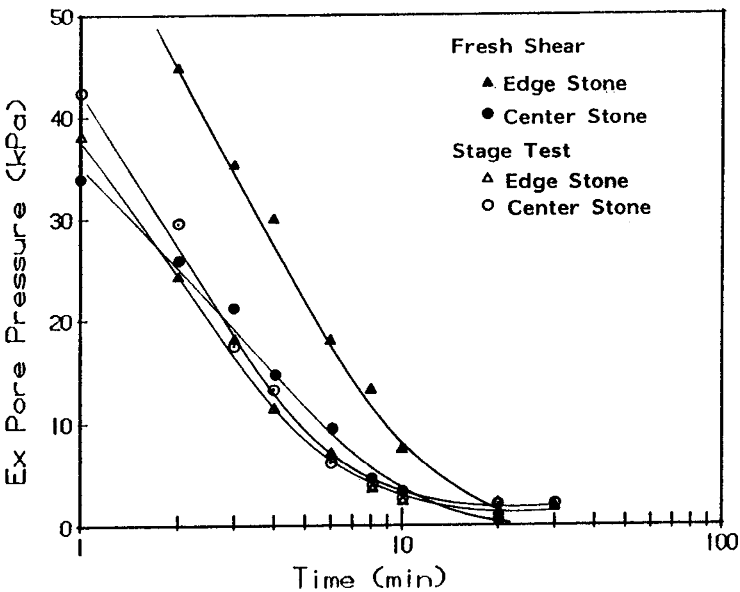

FIG. 5. - Post-Shear Phase Results

Shear Strength

Total Stress and Effective Stress

The results presented suggest that the distribution of pore pressures on the face of the shear plates during the shear phase of the tests may be complex and perhaps may be initially estimated as a triangular distribution, with a maximum value at the leading edge of the plate and a value of zero at the trailing edge. Therefore an approximate value for correcting total normal stresses to effective normal stresses may be taken by simply using the pore pressure measured at the center of the plate.

The results from tests conducted at both sites are summarized in Table 1 which presents both total and effective shear strength parameters. As anticipated, the general trend in results is an increase in friction angle from ϕ to ϕ' however, there doesn't appear to be a consistent trend in total and effective cohesion. For the clays tested, the magnitude of change in both friction angle and cohesion is quite small and probably within the error of reproducibility of results (7). Changes in friction angle and cohesion from total stress to effective stress should be expected to vary with stress history and OCR. Results of consolidated- undrained direct shear tests are also presented for comparison.

Stage Testing vs. Fresh Shear

For all test locations parallel tests were conducted to compare stage testing results with fresh shear testing results. These results are also presented in Table 1. At the first site, MHS, the effective stress friction angles obtained from fresh shearing were consistently higher than the total stress friction angle owing to higher pore pressures measured during fresh shear. While this was also the general trend at the second site the difference between ϕ and ϕ' is not as great.

A comparison between both total and effective friction angle between the stage tests and fresh shear tests shown in Table 2 indicates that while no consistent trend is clear, on the average the results are not substantially different. The mean value of total stress cohesion from all tests is about the same, however, at the first site the values were generally higher, while at the second site the values were generally lower. Effective stress cohesion values from fresh shear tests were all lower than stage test results, by a mean value of about 64%.

TABLE 1. - Summary of BST Results

Site	Depth	Stage Testing				Fresh Shear				Direct Shear	
	(m)	ϕ (deg)	c (kPa)	ϕ'	c'	ϕ	c	ϕ'	c'	ϕ	c
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
MHS	0.8	21.6	27.9	22.5	25.2	26.8	0	28.0	0	-	-
	1.5	28.7	2.1	30.5	6.0	21.0	4.1	27.2	0.6	24.3	37.2
	2.3	21.6	3.8	18.4	14.6	18.7	4.3	21.9	11.2	-	-
	3.0	23.6	8.8	24.1	16.1	14.2	10.5	17.3	15.9	25.6	26.9
RRC	0.8	32.5	14.6	32.5	14.6	28.0	10.7	28.1	10.6	-	-
	1.5	26.7	19.7	27.6	18.4	28.6	11.7	29.0	11.7	12.8	77.3
	2.3	24.5	16.0	25.4	16.0	24.2	11.7	25.8	11.7	-	-
	3.0	18.1	19.2	18.4	25.2	21.4	11.0	22.4	13.8	25.6	45.5

TABLE 2. - Comparison of Fresh Shear and Stage Tests

	$\frac{\phi_f}{\phi_s}$ (1)	$\frac{\phi'_f}{\phi'_s}$ (2)	$\frac{c_f}{c_s}$ (3)	$\frac{c'_f}{c'_s}$ (4)
Mean Value	0.94	1.02	0.98	0.64

f = fresh shear
s = stage testing

CONSOLIDATION CHARACTERISTICS FROM CONSOLIDATION PHASE

Results of the consolidation phase of the test may be useful for estimating consolidation characteristics of the soil. Objections could be voiced to any such possibility because of unknowns such as disturbance to the borehole wall, scale effects, directional testing, etc. (e.g. 3).

The movement of the shear plate against the wall of the borehole roughly models a rigid (albeit curved) impermeable footing test on the surface of a semi-infinite soil mass. The shape of the plate (L/B = 1.25) and other geometric conditions would suggest that the rate of settlement would more closely approximate three-dimensional conditions. Taking this into account, the solution presented by Gibson and McNamee (4) and discussed by Davis and Poulos (1) may provide a preliminary solution to obtain c_v, the one-dimensional coefficient of consolidation.

As shown in Fig. 6, the value of c_v may be estimated by obtaining the correct value of the time factor T_V at a corresponding value of time (t) and degree of settlement (U_S). The degree of settlement may be obtained from the consolidation phase of the BST by calculating U_S as:

$$U_S = 1 - u_E/u_{max} \qquad (1)$$

where: u_E = excess pore pressure at time t

u_{max} = maximum excess pore pressure

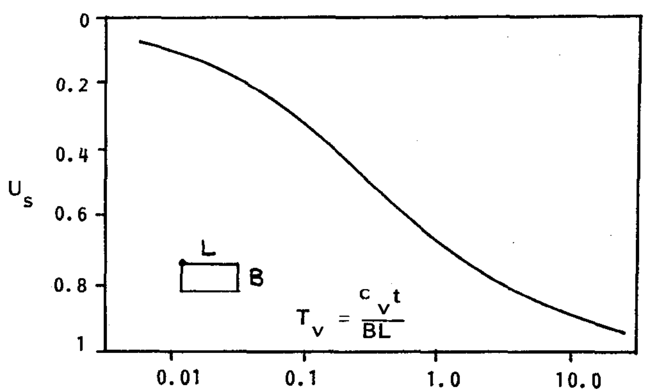

FIG. 6. - Degree of Settlement Beneath the Corner of a Uniformly Loaded Rectangle on the Surface of a Semi-Infinite Elastic Medium (1)

An initial comparison between c_v obtained with the BST and available laboratory one-dimensional consolidation tests indicates that the BST results underpredict c_v by about a factor of 5 over the same stress range. A more detailed comparison is currently underway.

SUMMARY

Excess pore water pressures are generated when using the BST in saturated clays. The complete test may be described in three phases during which pore water pressures are involved: (1) consolidation phase - during which pore pressures dissipate under constant applied normal stress; (2) shear phase - during which pore pressures are generated under increasing shear displacement up to a peak value, and (3) post-shear or reconsolidation phase - during which shear phase pore pressures dissipate under zero shear stress and constant applied normal stress. The magnitude of pore water pressures during each phase is probably a function of soil type, stress history, permeability, location of pore water pressure measurement and type of BST, i.e. stage test or fresh shear.

CONCLUSIONS

An investigation was conducted to determine the effect of pore pressure on the shear strength results obtained with the Borehole Shear Test in clays. Preliminary results may be summarized as follows:

1. During the consolidation phase of the BST excess pore water pressures are generated in saturated clays. Tests on unsaturated clays only indicated pore pressures at high values of applied normal stress.

2. Consolidation phase pore pressures are higher for fresh shearing compared to stage tests performed at the same applied normal stress. This may be in part related to a zone of loose material at the borehole wall.

3. Pore pressures across the shear plate estimated by measurements at two positions are more uniform for stage tests than for fresh shearing.

4. While the rate of pore pressure dissipation appears to be higher for fresh shearing, the total consolidation time is less for stage testing since the maximum excess pore pressure is less.

5. A consolidation time of at least 20 min. was necessary to dissipate excess pore pressures in the clays tested.

6. During the shear phase of the test, pore pressures across the shear plate are nonuniform and are generally higher at the upper part of the shear plate which may be an indication of plowing (edge effect).

7. For the clays tested, the total and effective stress shear strength parameters were not greatly different, however the difference was greater for fresh shear tests than for stage tests.

8. Following the shear phase of the test, up to 20 min. was required to fully dissipate pore pressures which may be an indication of reconsolidation or healing of the soil.

9. An initial assessment of consolidation phase curves modeled as the three-dimensional settlement of a footing appears to give reasonable estimates of c_v, the one-dimensional coefficient of consolidation.

APPENDIX-REFERENCES

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